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SPECIAL REPORT

INVESTIGATION OF ELECTRIFICATION OF POWDERS IN
FLOW THROUGH TUBES AND NOZZLES

I. A CHARGE ANALYZER

By

T. G. Owe Berg

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Contract DA-18-108-405-CML-829

Report No.   0395-04(08)SP   May 1963

ORDNANCE DIVISION

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Downey, California

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Investigations Under
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ABSTRACT

As a part of an investigation of the electrification of powders in flow
through tubes and nozzles, a charge analyzer has been designed, con-
structed, and tested.   The charge analyzer has two electrodes at
+1000 volts with respect to ground.   At a stationary state, the current
from each electrode is equal to the rate of deposition of charge.   The
two currents are recorded and integrated with a planimeter.   The
electrodes are weighed on a micro-balance for determination of the
amount deposited.   The nozzle is located at one end of the pair of
electrodes.

Experiments have been conducted with several airborne powders, in
the range 1 to 30μ of particle diameter, flowing through a hypodermic
needle of 0.8 mm diameter and 3 ft length of flow rates between 50
and 500 cc/min.   The average positive charge, the average negative
charge, and the average absolute charge are proportional to the square
of the flow rate.   The charge is all acquired in friction between the
powder particles and a deposit on the tube wall.   Average charges
up to 0.01 C/g have been measured.   The charge is smaller the greater
the extent of agglomeration of the powder.   It depends as much upon
agglomeration as upon the nature of the powder.

It follows that literature data on aerosol charges determined with
samples in slow rectified flow, e.g., by a capillary tube or a slit
system, are misleading and may be too low by many orders of magnitude.

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1.   INTRODUCTION

Powders flowing through pipes and nozzles acquire electrostatic charges
as a result of friction. The charges on individual particles may have
large positive and negative values, but the net charge of the powder is
usually small. There is a variety of effects of these charges, e.g.,
explosion hazard and agglomeration. They are therefore of technical as
well as general scientific interest.

The magnitude and the distribution of the charges depend upon the nature
of the powder and the flow conditions. These relations are currently
under investigation in our laboratory under contract with the U. S. Army
Chemical Center. The work includes the study of the general mechanism
of electrification and the determination of the charge situation with parti-
cular powders under particular flow conditions. This report covers one
phase of the work, namely the development of a technique for the study
of charges on powders flowing through a pipe and emerging from a nozzle.
In order to place this particular task in its context, a few comments on
the general program may be warranted.

As a result of the flow conditions at the wall and of attraction and ad-
esion between powder and wall, the wall of the pipe or nozzle becomes
coated with the powder material. The bulk of the powder particles
emerging therefore do not touch the wall but acquire their charges through
friction against this coat on the wall or against one another.[1,2] In
order to simulate these conditions, experiments have been conducted with
5mm glass beads rolling along a glass tube. The charge on each individual
bead is then recorded by means of a Faraday cage and a recording elec-
trometer. The results of this investigation have been reported else-
where [3,4]. In view of their bearing upon the subject of this report they
will be briefly summarized here.

The beads had a bimodal charge distribution, the net charge being close
to zero. Curves were plotted of average absolute charge q against time
interval between beads, time spent in the tube, and relative humidity of
the air. These curves showed simple relations. The charge q was pro-
portional to the square root of the frequency, i.e., the inverted value
of the time interval between beads. This is equivalent to proportionality
between charge and square root of flow rate. The same presentation was
tried for the average positive charge q_+ and the average negative charge
q_-, but these plots were not so simple. The ratio q_+/q_- and the percentage
of positively charged beads followed the same law, although these quantities

assumed constant values above a certain frequency [3]. q was also found to be a linear function of the square root of the time spent by each bead in the tube and of the square root of the relative humidity of the air at very low humidities and on the inverse value of this quantity at higher humidities [4]. These results permit a simple electrochemical interpretation [3-5].

In addition to elucidating the mechanism of electrification, these experiments are very helpful in the development of an experimental technique for the study of electrification of flowing powders. First of all, the initial charges of the beads had no effect upon the final charges as the beads emerged from the tube. Consequently, in the study of electrification of flowing powders it is not necessary to remove the charges from the powder before it enters the pipe. This conclusion is borne out by observations with flowing powders. Second, the charge of the beads, and presumably also of the powder, is adequately described by the averages of positive, negative, and absolute charges and by the numbers of positively and negatively charged particles. This conclusion is also borne out by the experiments with flowing powders.

It follows that the objective at hand, the effects of the properties of the powder and the flow conditions upon the electrification of flowing powders, requires an experimental technique that separates positive, negative, and neutral particles and measures their relative amounts and the charge per-gram of the positive and negative fractions. A complete analysis in terms of charge and particle size distributions is not required by this objective. In particular, the particle size or the particle size distribution would be among the properties of the powder to be varied and independently determined.

An important consequence is that the observation of individual particles and the determination of charge and size of individual particles are not required by the objective. It is our experience that the observation of individual particles, e. g. , in the assessment of aerosol particle size, is almost prohibitively tedious and strenuous. The techniques for charge measurements described in the literature are almost all based upon the observation of individual particles. This may account for the scarcity of data of the type required by the objective of this investigation.

Reference may be given to an ingeniously simple technique for charge measurements on flowing powders developed by Nash et al [6]. This technique meets the requirements just outlined, but it is limited to very high densities of the stream of powder and to powders of uniform size.

The powder flows freely through a nozzle, e.g., in the bottom of a container, and between two plane electrodes with a suitable voltage between them. The cylindrical stream of powder is spread out as a fan of a density that varies with the distance to the vertical. A photograph is taken of this fan at a stationary state. The photograph is evaluated in a recording densitometer. The deflection of the densitometer is proportional to the blackening of the film and thereby to the density of the fan. The record thus gives a picture of the charge distribution in the powder. For a uniform particle size, this picture comes close to the actual charge distribution.

It is easy to criticize this technique. Variations in particle size, turbulence of flow, and velocity components in the direction of the field are obvious sources of error. The error is little, however, as compared to that of a technique that involves sampling of the flowing powders. As already pointed out, the charges on the powder when it emerges from the pipe are independent of the charges on the powder when it enters the pipe. This applies equally to the flow of a sample through a sampling tube. Consequently, techniques based on sampling of the powder lead to errors in the order of magnitude of the charge. Indeed, the measured charge of the sample may not be related at all to the charge of the sampled powder. Hence, we may conclude the technique of Nash et al is comparatively accurate. A careful search of the literature has failed to reveal any other technique that does not involve sampling.

Nevertheless, the error of measurement limits the technique of Nash et al to qualitative or semiquantitative evaluation of the effects of powder properties and flow conditions upon the charge. Even so it has yielded valuable information on these effects. But the error of measurement does not permit quantitative measurements of the accuracy required for the study of the mechanism of electrification.

Our technique was conceived and developed simultaneously and independently. It is similar to the technique of Nash et al in the respect that the entire stream of powder is analyzed. But it differs in the method of analysis of the stream of powder. Our charge analyzer has two collector electrodes, on which all the charged particles are deposited, and a neutral filter, on which the neutral particles are collected. The collector electrodes are connected to batteries through high resistances. At a stationary state, the current flowing through each resistor is equal to the rate of deposition of charge on the corresponding collector electrode. The currents from the two collector electrodes are recorded. Integration of the records gives the two total charges. The collector electrodes are

then weighed for determination of the amount of powder deposited. In this way the average positive charge per gram and the average negative charge per gram are determined.

This technique is accurate because it involves the measurements of weight and current only, both being inherently accurately measurable. It suffers, however, from the difficulties encountered in measurements at high resistances, namely, maintenance of good insulation and sensitivity to mechanical vibrations. These difficulties have been fairly successfully resolved. The technique has in addition the advantage of high speed. Two operators, one weighing, the other operating the analyzer and the flow system, can make one determination in 20 minutes.

The design and construction of the charge analyzer are described in Section 2. Results obtained in testing the charge analyzer are given in Section 4.

2. DESIGN AND CONSTRUCTION OF THE CHARGE ANALYZER

A diagram of the charge analyzer is given in Figure 1. The air stream carrying the powder particles enters through a hypodermic needle, passes between two collectors, and leaves through a filter paper. The collectors are connected to two batteries of ± 1000 volts with the mid-point connected to ground. The charged particles deposit on the collectors, and the neutral particles on the filter paper. The deposits on collectors and filter paper are weighed on an Ainsworth microbalance. The charges deposited on the collectors are bled off to ground through resistances of the order of $10^{10}\,\Omega$, and the voltage drops across the resistances are recorded. Two General Radio dc amplifiers and two Esterline-Angus recorders are used, one set for each collector. The resistances are the input resistances of the amplifiers. These can be selected between 10^6 and $10^{11}\,\Omega$. The dc amplifiers have a sensitivity range from 30 mV to 10 V in steps of a factor of 3. In order to avoid electrical coupling between the collectors, each collector is surrounded by a ground-connected shield with a slot along the middle to admit the particles onto the collector. To the same purpose, the batteries and the leads to the collectors are carefully shielded

Figure 2 shows the collector and shield assembly. The collector electrode is mounted on a strip of 0.6 mm brass shim, which slides in grooves in the shield, and is insulated from the brass shim by a 1 mm thick
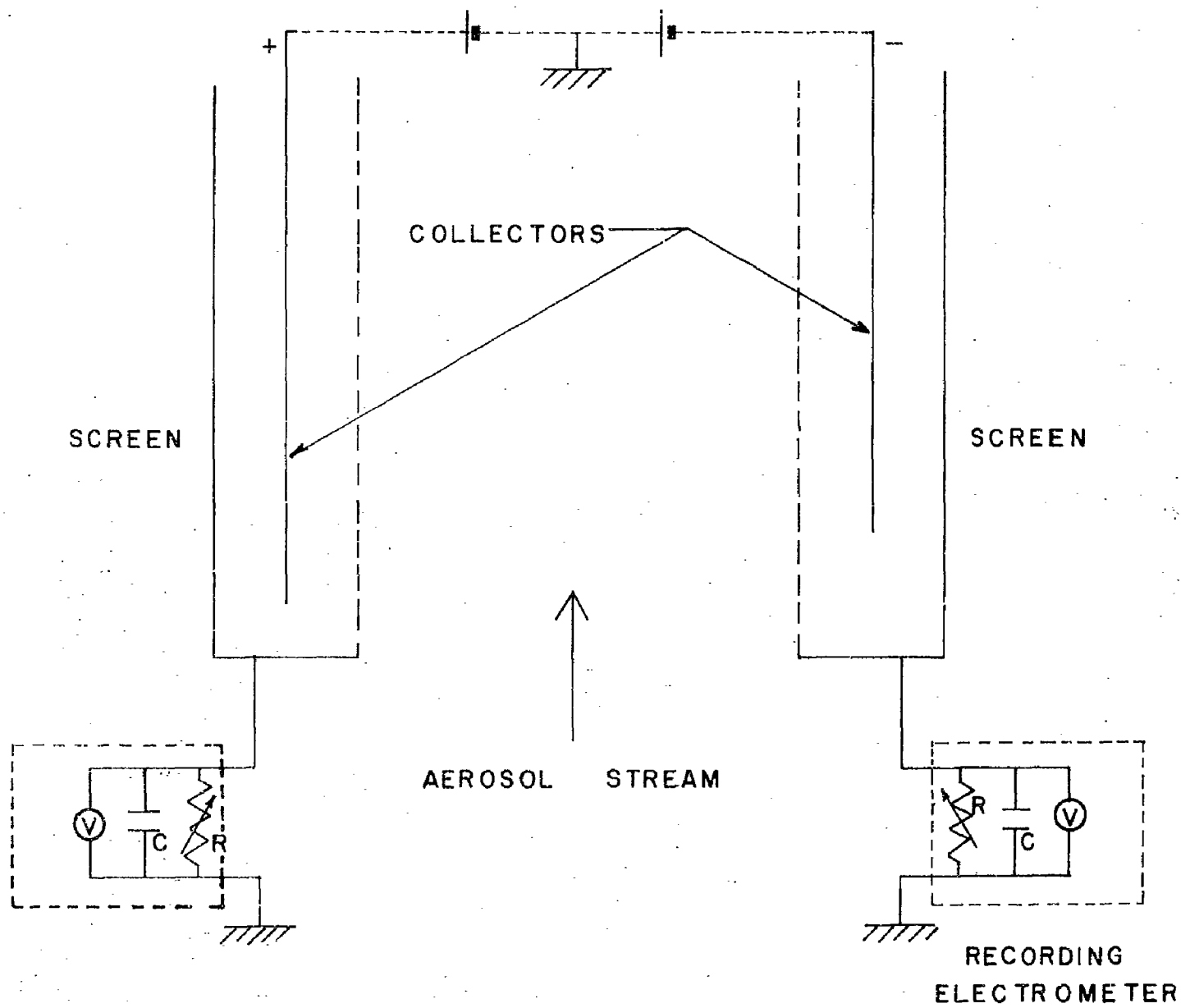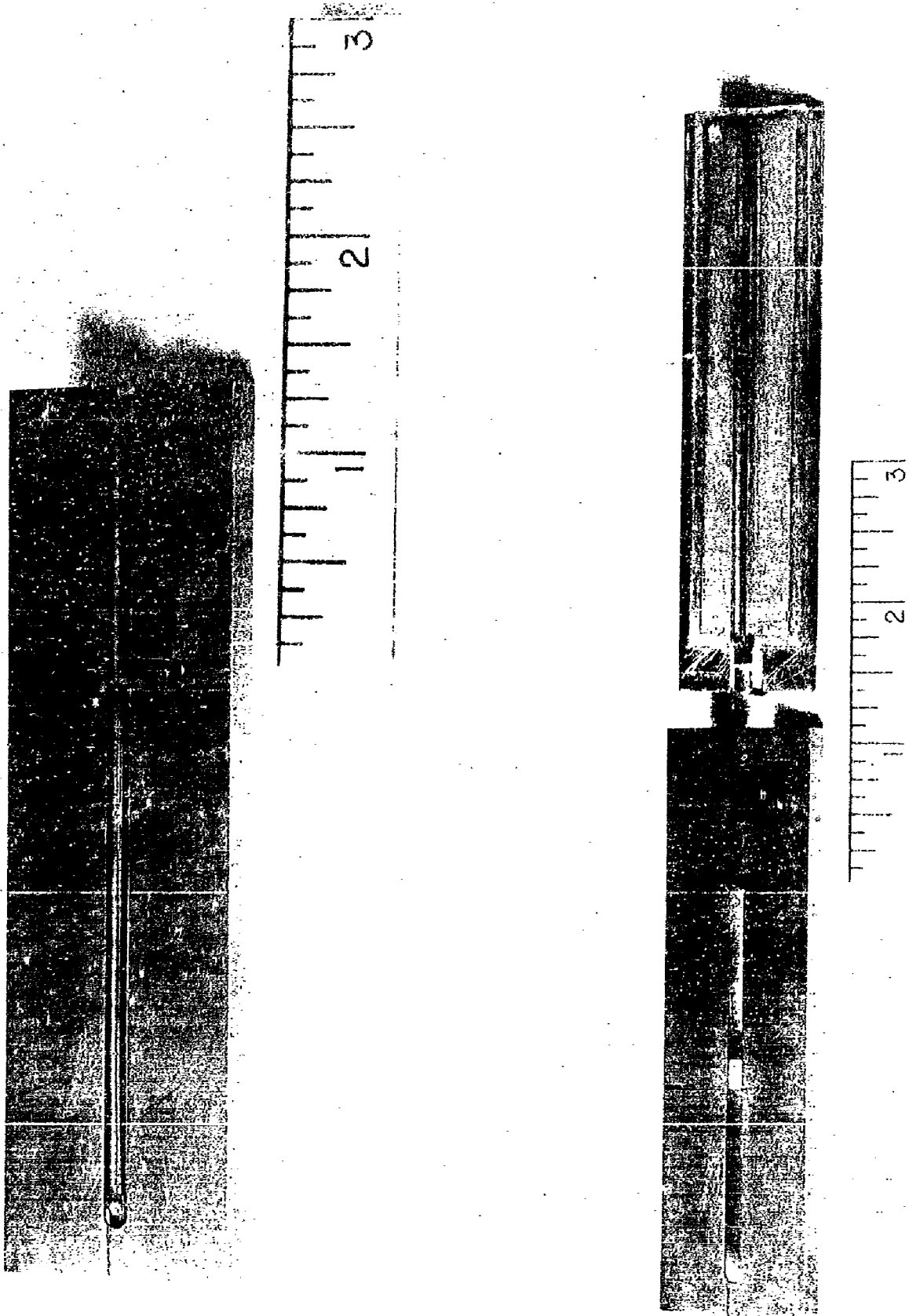
Figure 1. Diagram of Charge Analyzer.

Figure 2. Collector and Shield Assembly.

plexiglass sheet. The collector electrode is cemented to the plexiglass, and the plexiglass is cemented to the brass shim. The collector electrode has the shape of a 1 mm wide, 3 mm high ridge of copper shim, on-which almost all of the deposit is collected, and an aluminum painted area of the plexiglass adjacent to it for collecting such particles as may miss the copper ridge. The copper ridge ends with a piece of copper wire that makes contact with a spring contact in the base of the analyzer. The purpose of the ridge is to give a field concentration in the slot in the shield, into which it penetrates. As a result of this field concentration, particles that would otherwise have deposited on the shield are pulled through the slot onto the collector. The deposit on the shield, at the edge of the slot, has been negligible in the experiments made so far with flow rates of up to 500 cc/min. The shield is machined out of 3 mm sheet copper. The slotted side is 1 mm thick, the width of the slot is 3 mm, the thickness of the sides holding the collector is 2 mm. The distance between the collector and the slotted side of the shield is 2 mm. The length of the assembly is 100 mm. The assembly is rugged and maintains the collector straight and at a well defined distance from the shield.

The collector and shield assemblies slide into grooves in a ground-connected heavy brass frame shown in Figure 3. This mounting assures that each assembly is held straight and in a fixed position. The distance between the shields is 4 mm. The brass frame is soldered onto a brass cylinder. Electrical connection to the collectors is effected by spring contacts mounted on plexiglass insulators with longest possible creep paths to the brass. The leads are clamped in plexiglass blocks screwed onto a 5 mm brass plate at the other end of the brass cylinder. They terminate in banana contacts that plug into connectors with the batteries.

The hypodermic needle, through which the powder is introduced, is inserted in a snug hole in the brass frame. It is sealed by the compression of a rubber gasket.

The frame is shielded by a copper cylinder that screws onto the brass cylinder. The filter holder screws onto the other end of the copper cylinder. The filter paper rests on a flat brass screen, the edge of which is pressed against a ring at the end of the copper cylinder. Sealing is effected by a conical rubber gasket. The filter holder terminates in a 6 mm brass tube that connects to a flow meter and a pump.
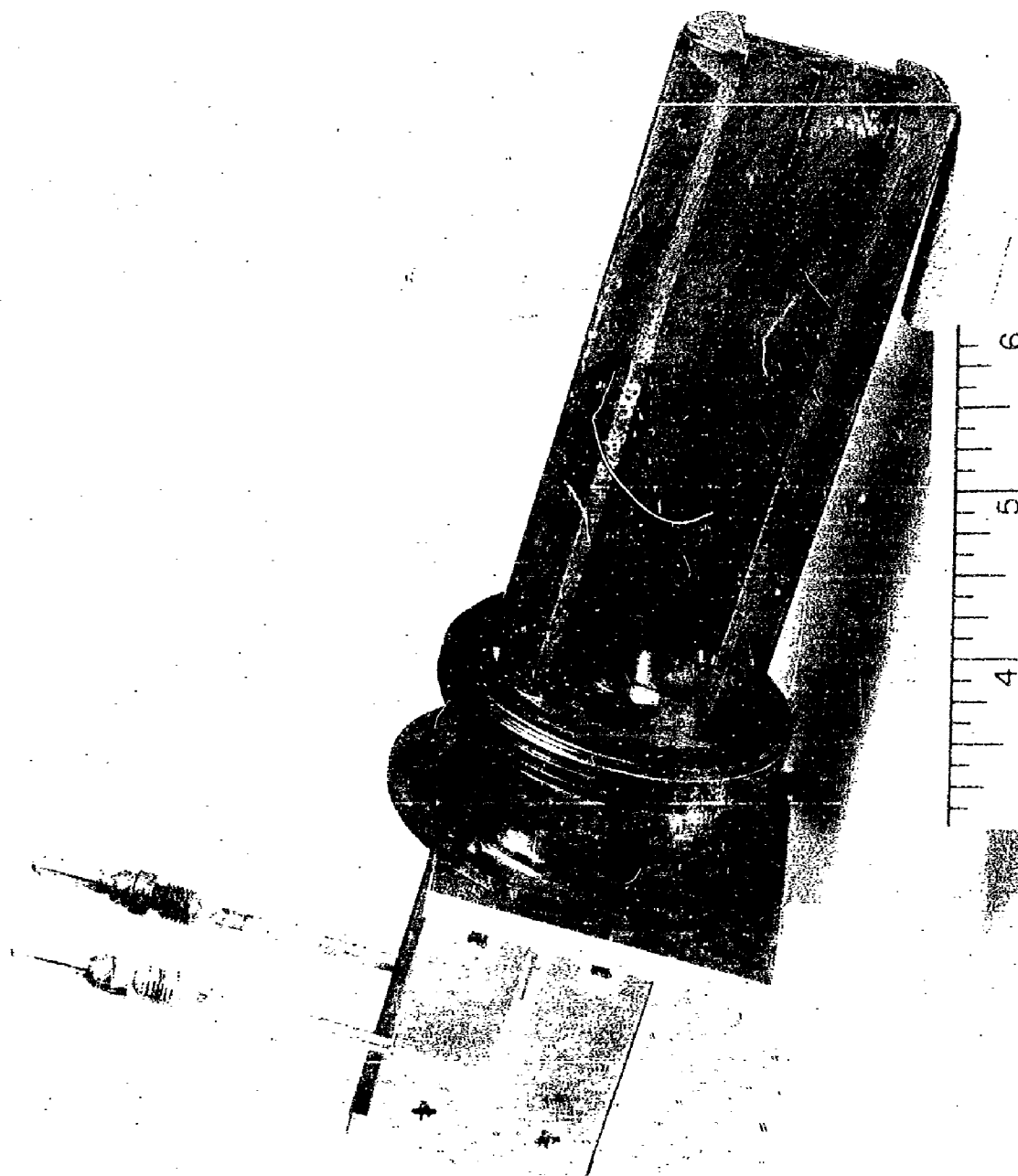
Figure 3. Photograph of Analyzer with One Collector and Shield Assembly in Place.
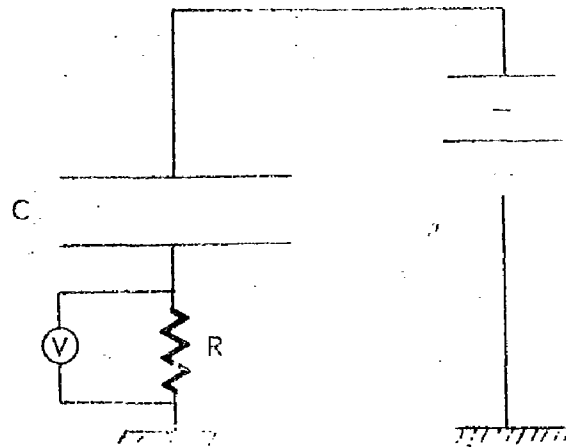
Figure 4.

Figure 4 shows a simplified diagram of one collector circuit. It consists essentially of a capacitance in series with a resistance and a battery. The charge is deposited on one electrode of the capacitance (the collector). At a stationary state, the current in the circuit is equal to the rate of deposition of charge. In a transient state, at start and end of a run, the current is, of course, affected by the time constant RC of the circuit. This time constant is of the order of 1 second at $10^{10}\Omega$, and the delay at beginning and end is therefore not important over a 60 second run. The time constant causes a smoothing of the recorded current, which is of advantage in planimetering the record for determination of the total charge collected. The distortion of the current record at beginning and end does not materially affect the area of the current record.

The current is also affected by changes in the capacitance at a constant charge. Consequently, the instrument is inherently sensitive to vibrations, and the sensitivity of the charge measurement is determined by the noise level introduced by vibrations. Accordingly, great pains have been taken to eliminate the effects of vibrations of the building. Thus, the charge analyzer itself has been constructed rigid and to close tolerances of the grooves in the frame and in the shields. The leads to the batteries are well supported 2 mm copper wires. A necessary precaution against vibrations is to avoid the use of coaxial cables, particularly flexible coaxial cables. Rigid coaxials built from brass tubing and brass rod with telescope junctions were tried. It was found that it was best to use no cable at all but to plug the amplified input connector directly into the connector on the battery box.

Another disturbance is caused by poor insulation. A constant insulation resistance of a magnitude of 100 times the measuring resistance introduces a negligible error of 1%, and the constant current through it can be compensated for by the zero adjustment of the amplifier. Constant insulation resistances encountered are generally high enough. Variable insulation resistances are more harmful since they increase the noise level and cause drift of the instrument. These are occasionally produced by dirt settling on insulators, particularly the connectors between amplifier and battery. The most important cause of poor insulation is moisture. It was found necessary to use dry air in the analyzer and as carrier of the powder, particularly at high sensitivity settings of the amplifiers. The insulation resistance did not affect the measurements once it was learned how to maintain good insulation.

With the precautions mentioned the instrument could be set at 30 mV and $10^{11}\Omega$ with a tolerable noise level. This setting corresponds to full deflection of the recorder for 3×10^{-13} amps.

3.   TESTING OF THE CHARGE ANALYZER

The charge analyzer was tested by measurements on powders of MgO, NH4Cl, polyvinyl chloride, and Buerker's powder. The nominal particle diameter of the first three powders is approximately 1 μ, but owing to agglomeration, the actual particle size was much larger, including particles of about 10 μ. Agglomeration was particularly extensive in the polyvinyl chloride, where hardly any small particles remained unagglomerated. It was least with MgO. Buerker's powder is a mixture of 1 part of carmine (1 μ), 9 parts of flower of sulfur (1 to 30 μ), and 5 parts of lycopodium (32 μ). This powder was developed for the determination of the polarity of charged objects, negative objects attracting the yellow components and positive objects attracting the red component. The lycopodium is added as a deagglomerating agent[7]. However, agglomeration is extensive, and the lycopodium particles are coated with carmine.

The airborne powder was sucked into the analyzer at different pumping speeds between 50 and 500 cc/min through a hypodermic needle of stainless steel. In these tests, the length and the diameter of the tubing were kept constant at 3 feet and 0.8 mm, respectively

The Buerker powder and the polyvinyl chloride powder were handled
with air conducted over Dryerite. The MgO was produced in ambient
air. The NH_4Cl was produced from the vapors of aqueous solutions
of NH_3 and HCl and was consequently suspended in air nearly saturated
with water vapor. This led to poor insulation in the charge analyzer,
but the NH_4Cl was highly charged and could be analyzed at a comparatively
small input resistance of the amplifier, $10^8 \Omega$. The MgO was still
more charged and was analyzed at the same resistance, $10^8 \Omega$.

Different techniques were used for mixing the powders with air and
making them airborne. The MgO was produced by burning a strip of
Mg metal in a glass cylinder. NH_4Cl was produced by blowing HCl
vapor into a chamber, into which HN_3 vapor had been blown previously.
Buerker's powder was stirred up in a rotating glass drum and blown
into a vertical brass cylinder, 2.5 in. in diameter and 5 feet tall, at an
air velocity of 4000 cc/min. The latter method was tried for dispersing
the polyvinyl chloride, but the material agglomerated very badly and
stuck to the wall of the drum. Whatever material reached the brass
cylinder stuck to the wall. Another method was then adopted, shown
in Figure 5. The powder is poured into a brass cylinder, diameter
1.5 in., length 6 in., that is suspended in rubber bands and shaken
by an excentric arm on a motor shaft. Air is blown into and through
the tube at approximately 2000 cc/min.

Figure 6 shows a typical current record. The areas of these records
were measured with a planimeter. The weight of the deposit was be-
tween 0.1 and 1 mg. Ordinarily, a deposit of this size was obtained in
one minute. At low particle densities, it took two minutes at the low-
est flow rates. The following quantities were determined:

weight of positive deposit in one minute w_+

weight of negative deposit in one minute w_-

total weight of deposits in one minute $W = w_+ + w_-$

positive charge collected in one minute Q_+

positive charge per gram of positive deposit collected in one minute
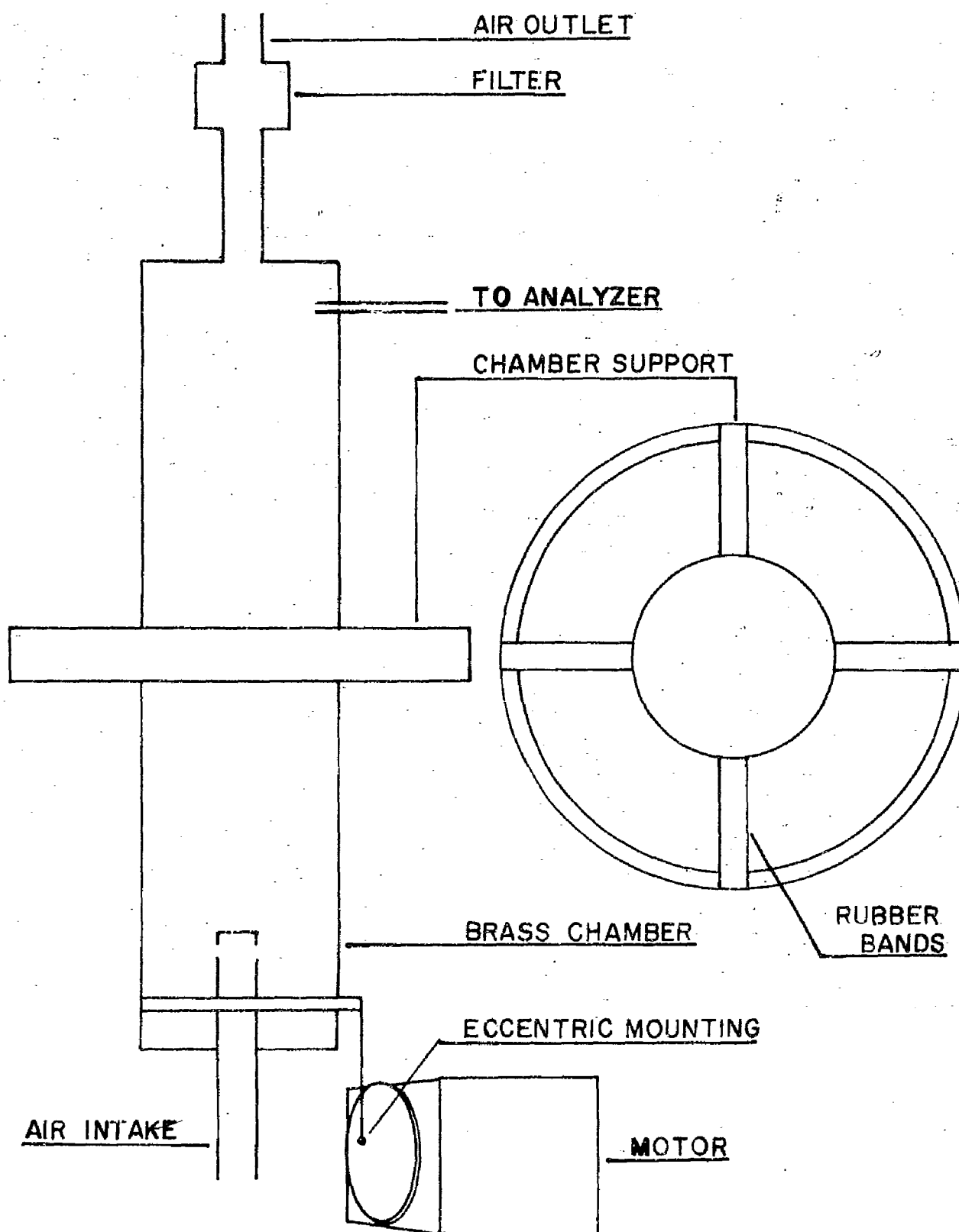
$$q_+ = \frac{Q_+}{w_+}$$

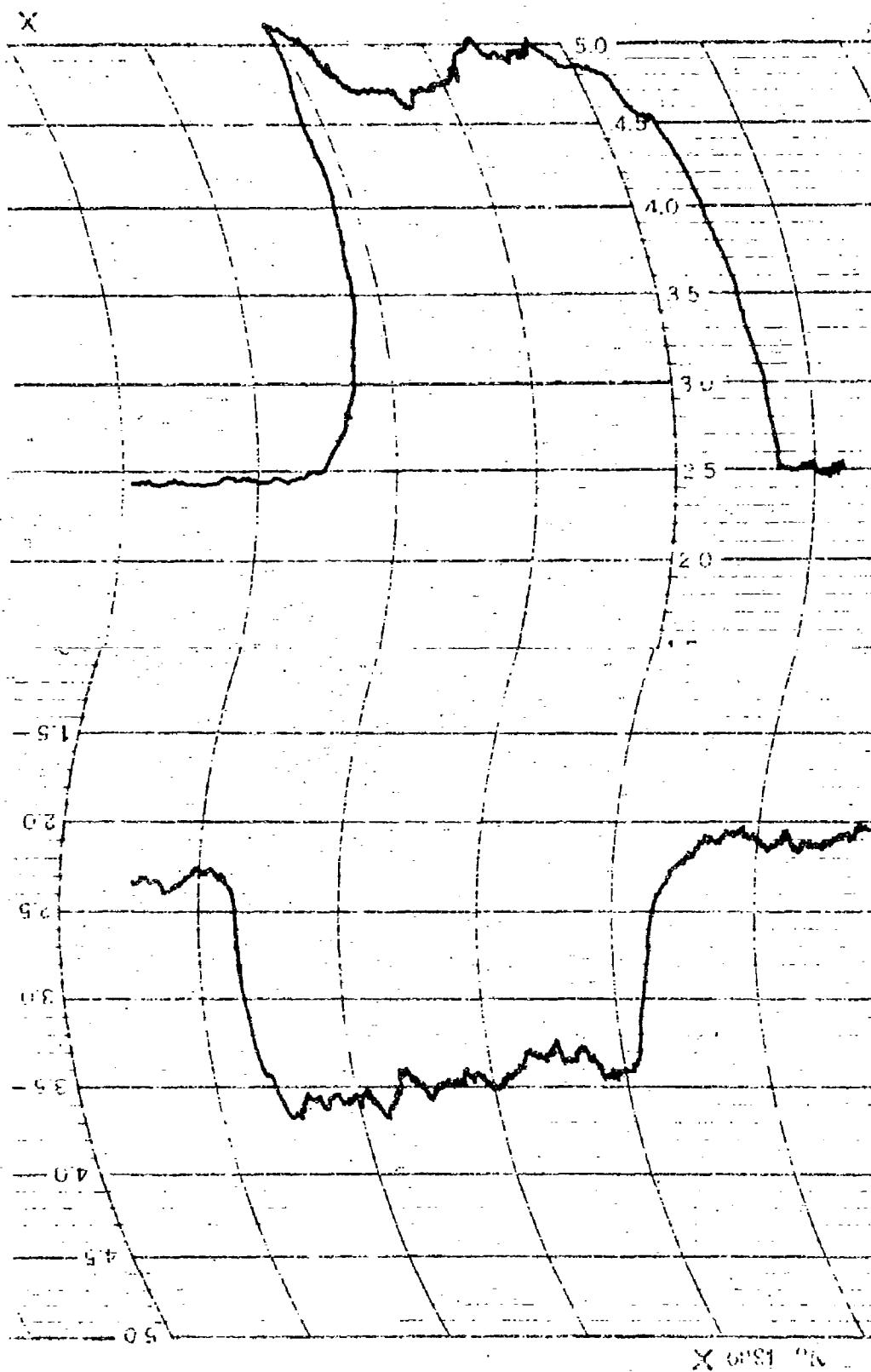Figure 5. Aerosol Generator Used with Polyvinyl Chloride.

Figure 6. Typical Current Record.

negative charge collected in one minute Q_-

negative charge per gram of negative deposit collected in one minute

$$q_- = \frac{Q_-}{W_-}$$

total absolute charge collected in one minute Q

absolute charge per gram of total deposit collected in one minute

$$q = \frac{Q}{W}$$

In no case was there a weighable amount deposited on the filter. There were thus very few neutral particles.

4.   TEST RESULTS

Since all the particles in the sample are deposited on the two collectors the total weight deposited in one minute, W, is proportional to the flow rate v, provided that the density of the aerosol expressed as weight of solid per volume of air is constant. Plots of W against v are given in Figure 7. The density variations are supprisingly small, although there are noteworthy deviations from the straight lines in several instances. Thus, the data for Buerker's powder indicate two slightly different densities.

This simple relation does not necessarily hold for the positive and negative deposits separately, for the charge distribution may depend upon the flow rate. With one constituent of the powder, it turns out that w_+ and w_- are proportional to v as shown in Figures 8 to 10. But for Buerker's powder, Figure 11, w_-, which is small and does not noticably affect the plot of W, reaches a constant level at 100 cc/min. It appears that the negative carmine attaches itself increasingly to the positive sulfur and lycopodium as the charges increase with the flow rate.

The charge depends upon the flow rate as to both magnitude and distribution. Figure 12 shows plots of the absolute charge per gram, q, as a function of v^2. For MgO and polyvinyl chloride, q is closely proportional to v^2.
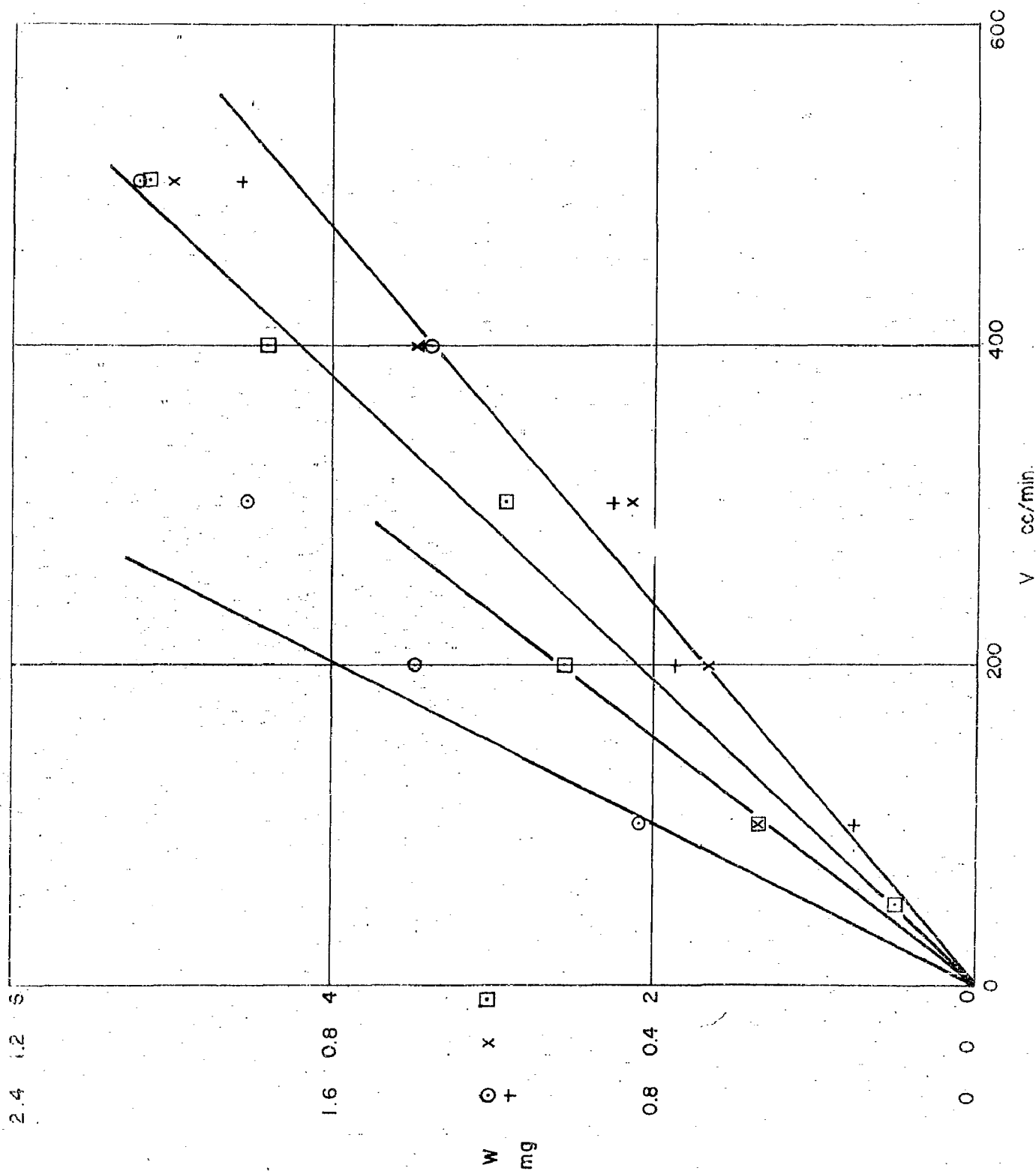
Figure 7. Total Weight Deposited in One Minute, W, as a Function of the Flow Rate V. NH_4Cl; X NH_4Cl; + Polyvinyl Chloride; $\square$ Buehler's Powder.

Figure 8. Positive Deposi. w_+ (x) and Negative Deposit w_- (⊙) in
One Minute for MgO as Functions of Flow Rate v.
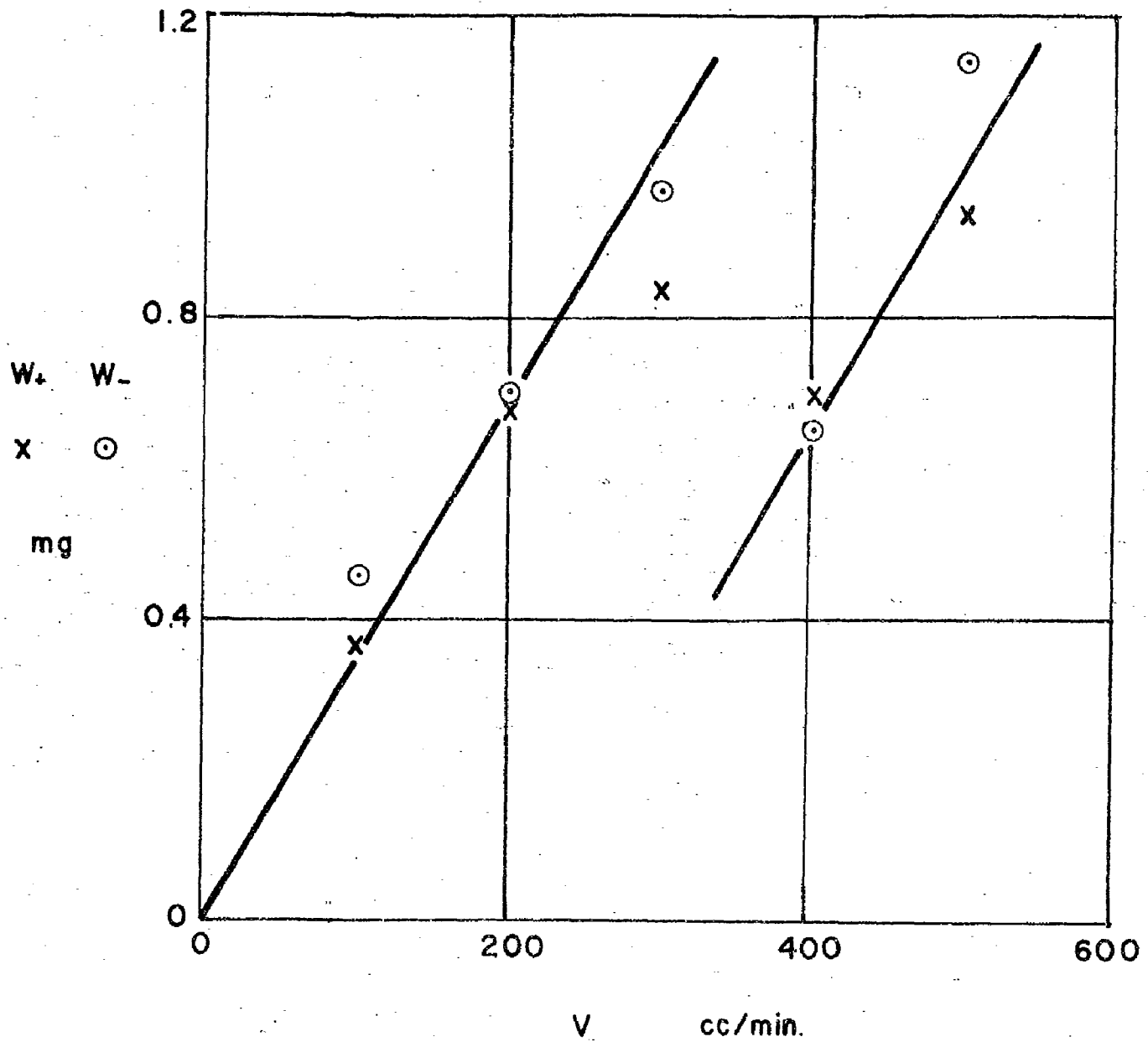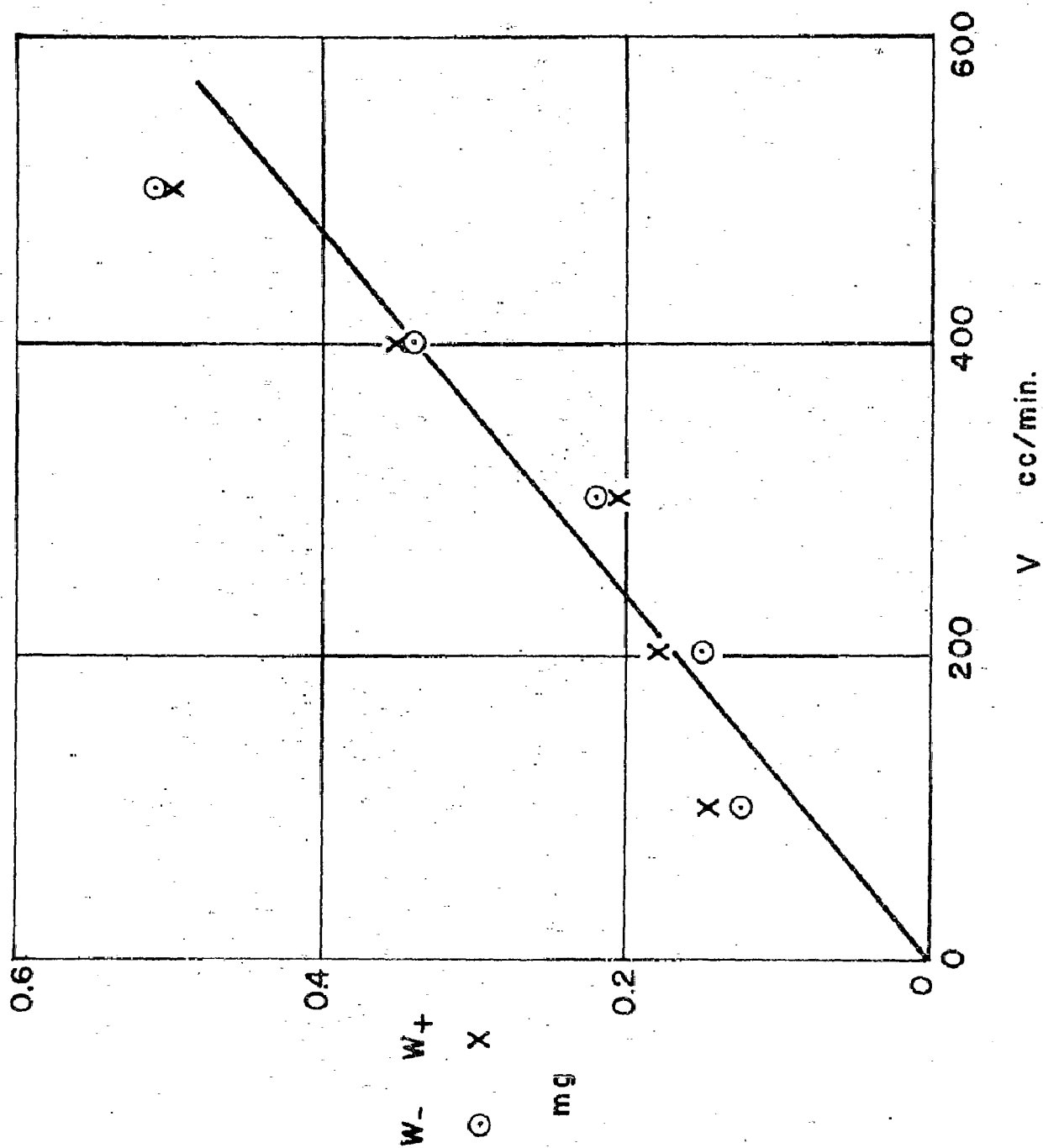
Figure 9. Positive Deposit w_+ (×) and Negative Deposit w_- (⊙) in One Minute for NH_4Cl as Functions of Flow Rate v.

Figure 10. Positive Deposit w_+ (✕) and Negative Deposit w_- (⊙) in
One Minute for Polyvinyl Chloride as Functions of Flow Rate v.
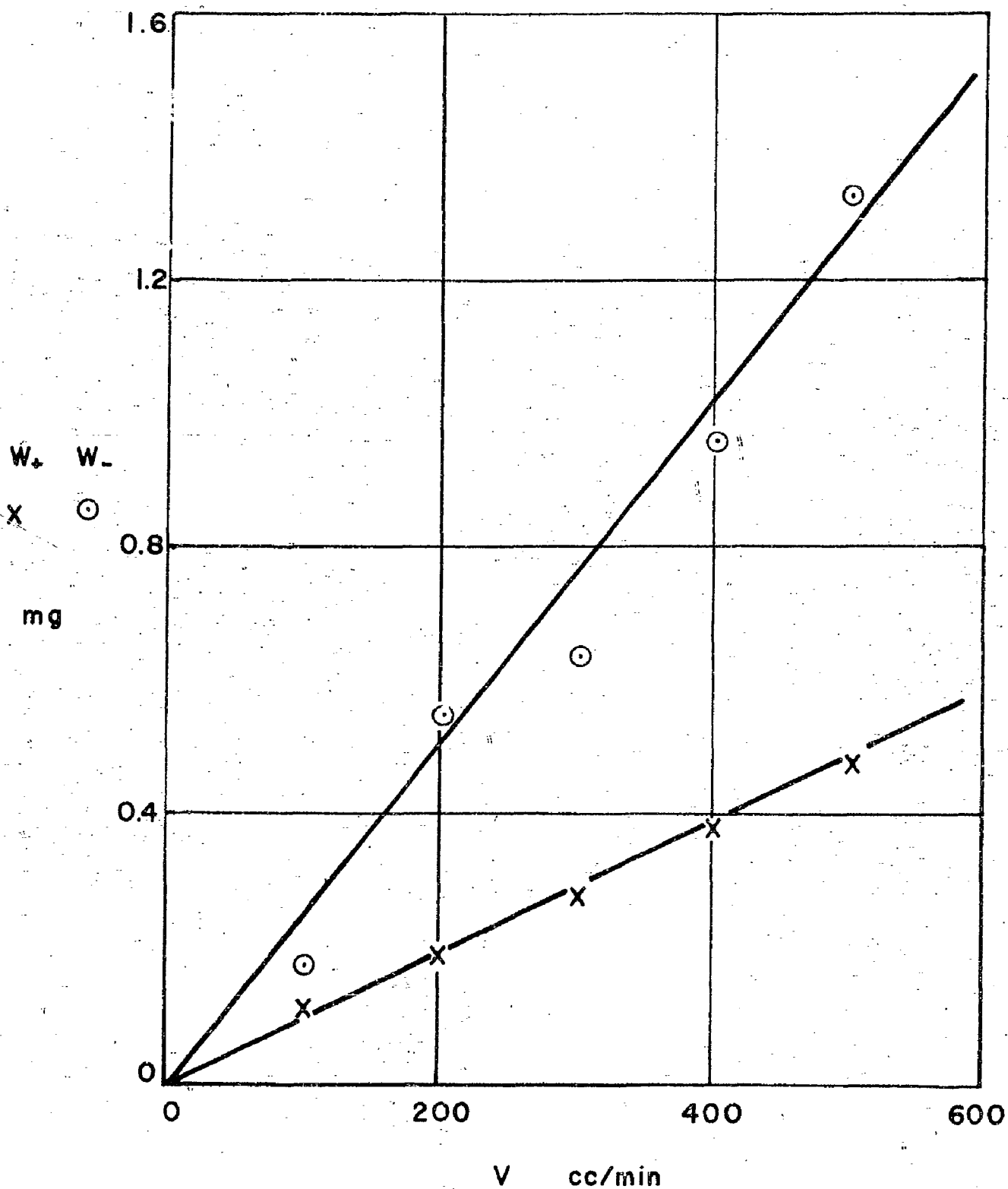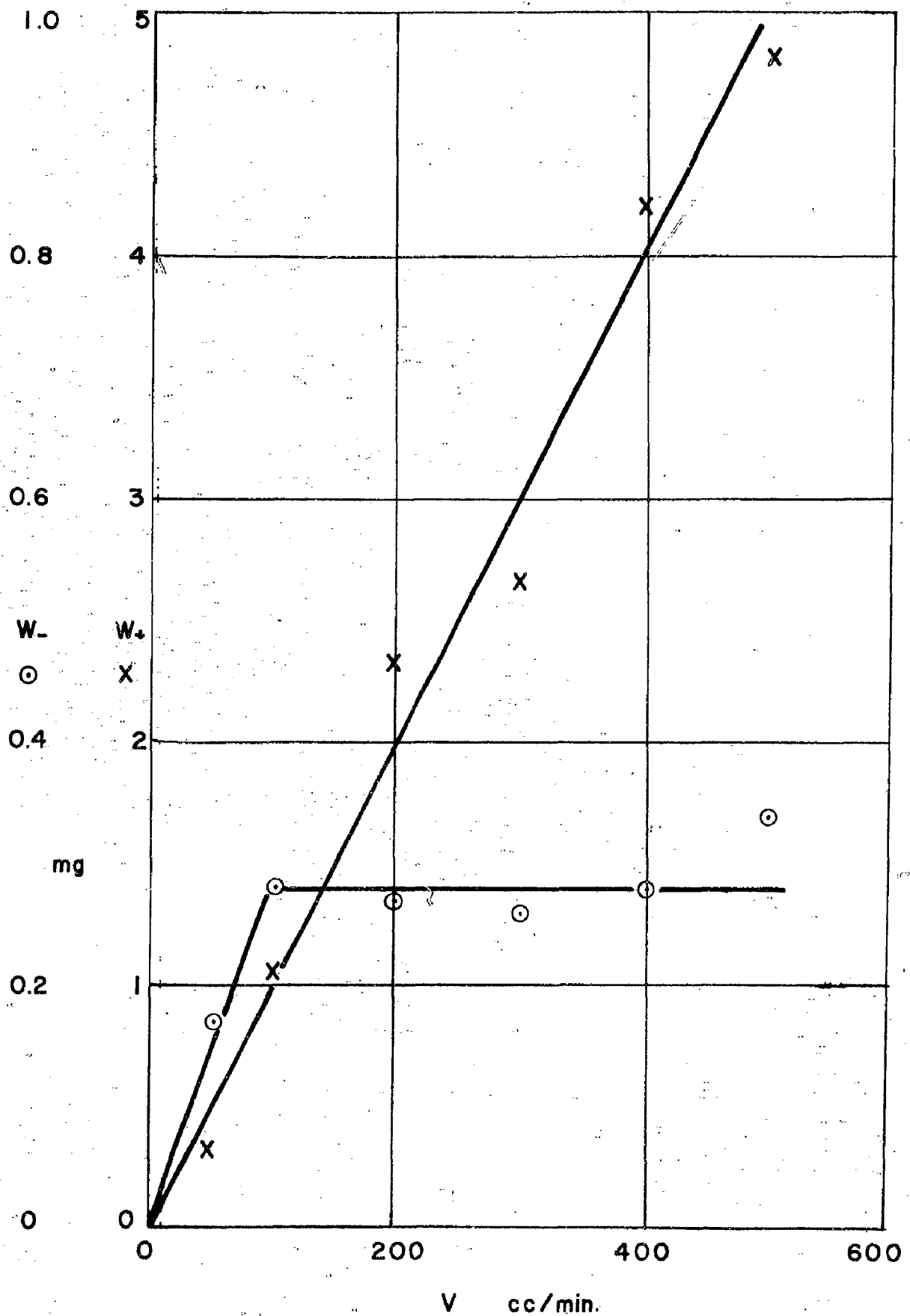
Figure 11. Positive Deposit w_+ (×) and Negative Deposit w_- (⊙) in One Minute for Buerker's Powder as Functions of Flow Rate v.
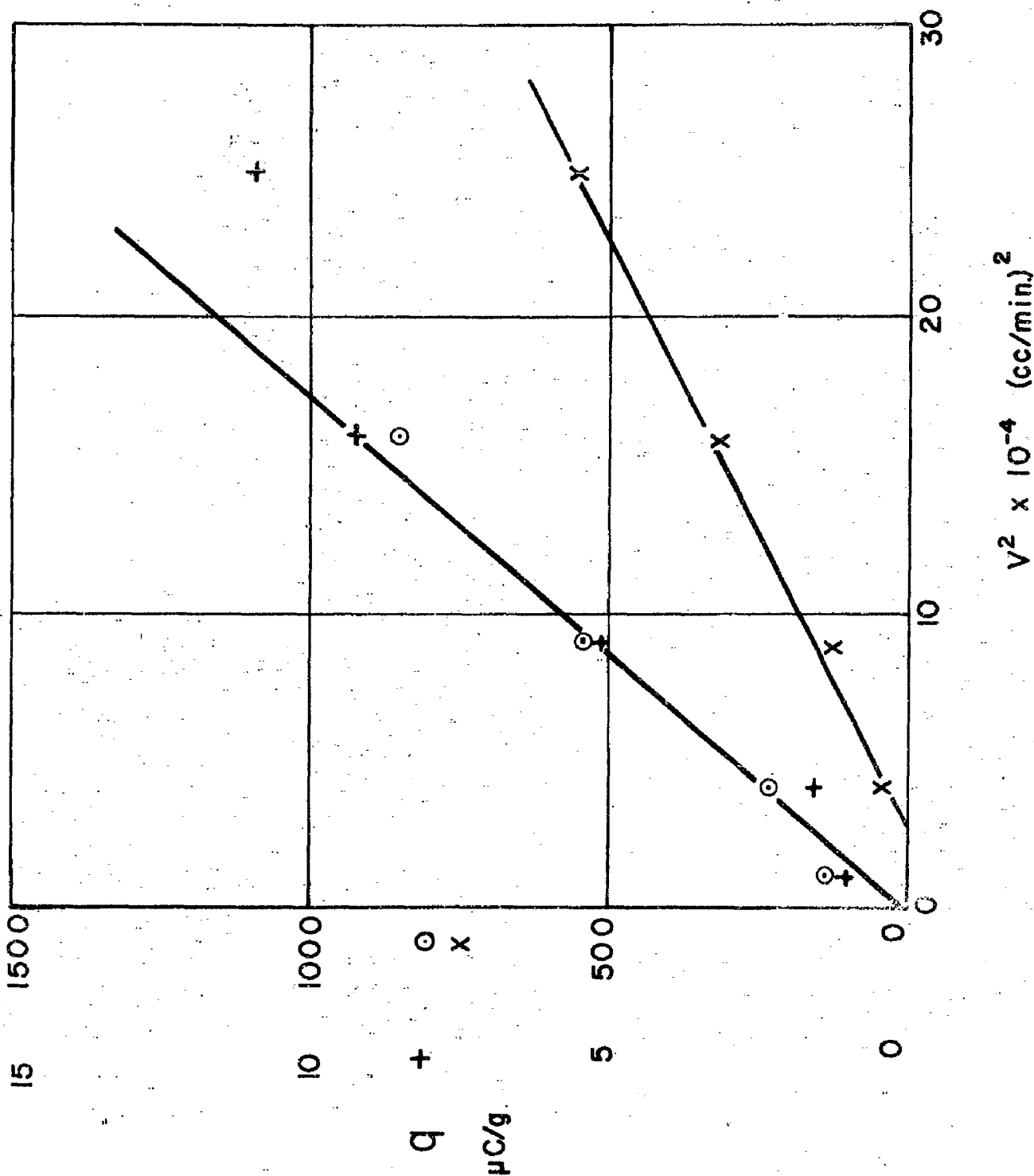
Figure 12. Absolute Charge per Gram, q, as Function of Square of Flow Rate v². ⊙ MgO, X NH₄Cl + Polyvinyl Chloride.

Better plots are obtained for the positive and negative charges separately, Figures 13 and 14. For MgO, NH_4Cl, and polyvinyl chloride, q_+ and q_- are proportional to v^2. For NH_4Cl, the data for q_- are inconclusive. The data for Buerker's powder, Figure 15, indicate that both q_+ and q_- are proportional to $\sqrt{v}$.

An important result is that the plots of q, q_+, and q_- extrapolate to zero at $v \geq 0$. Hence, there is no charge at zero flow velocity. This was also found to hold for the charges on glass beads referred to in Section 1. In all these cases, the charges measured are all acquired by friction in the tube and are entirely independent of the state of charging before entering the tube.

It is interesting to note that q, q_+, and q_- are essentially independent of the density. For instance, the density of the MgO sample at 400 cc/min is less than half the normal density, but the values of q, q_+, and q_- do not deviate appreciably from the normal values. It follows that the charges are acquired in collisions between particles and tube wall and not in collisions among the particles themselves.

Buerker's powder is an apparent exception to these rules. Figure 16 shows a plot of Q against v. This plot is a good straight line. Comparing this plot with that of W against v in Figure 7, one finds that q is independent of v and that q increases with decreasing density. Figure 17 shows a plot of q against v. There appears to be two constant values of q, namely $q = 4.5 \mu C/g$ at the higher density and $q = 6.2 \mu C/g$ at the lower density. On the other hand, the plots of Q_+ and Q_- in Figures 18 and 19 indicate that Q_+ is proportional to v and q_+ therefore independent of v, whereas Q_- is proportional to $\sqrt{v}$ and q_- therefore also proportional to $\sqrt{v}$. However, both q_+ and q_- seem to be proportional to $\sqrt{v}$, Figure 15. The data are not quite conclusive, and their proper presentation and their interpretation should be deferred until more extensive experience has been gained with composite powders.

5. DISCUSSION OF RESULTS

The data obtained show conclusively that both charge and charge distribution depend upon the flow rate. In particular, there is no charge at zero flow velocity, and all of the charge measured is acquired in the flow through the tube, notably by collisions between particles and tube wall.
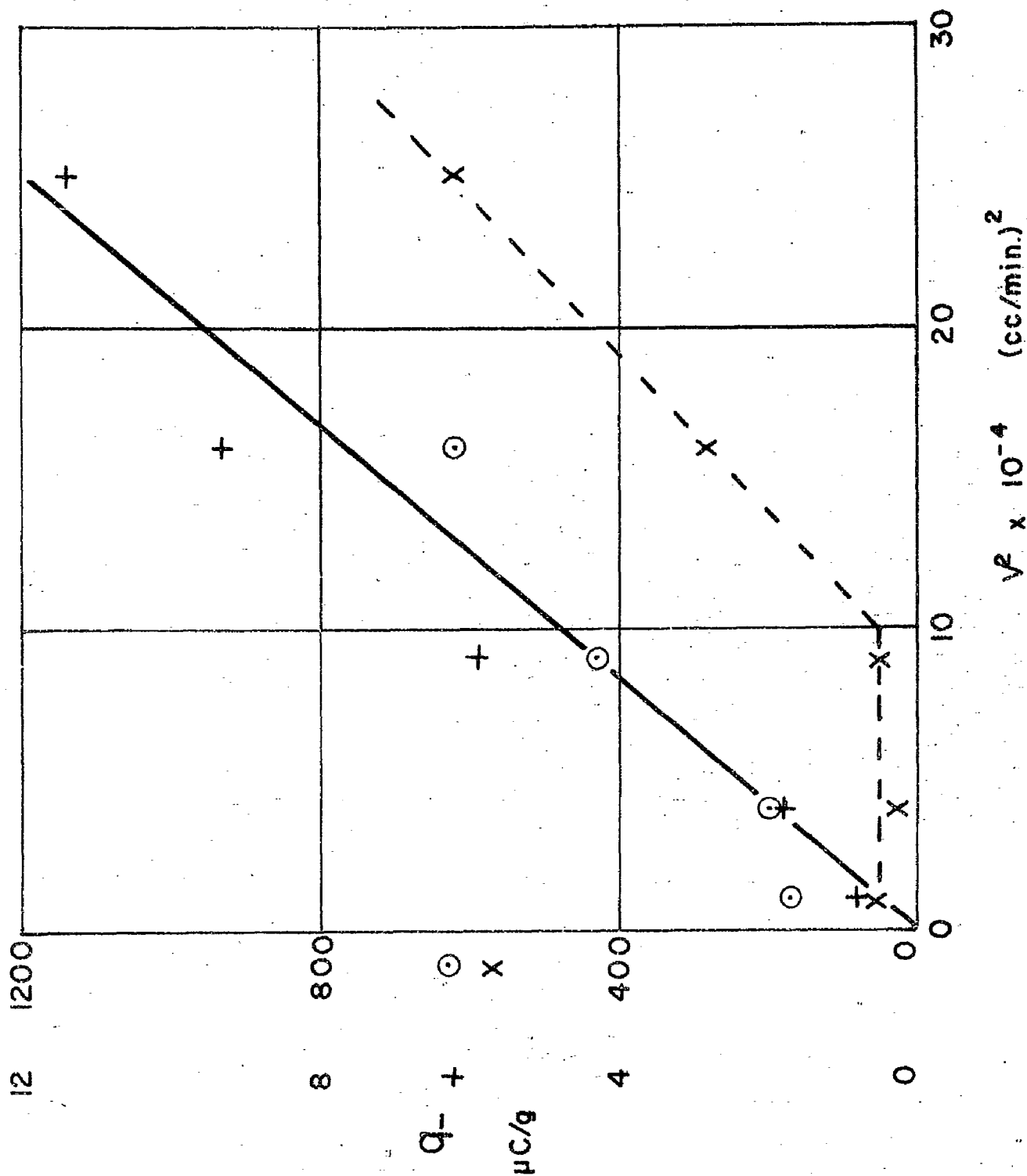
Figure 13. Negative Charge per Gram Negative Deposit, q, as a Function of Square of Flow Rate, V^2. $\odot$ MgO. X NH_4Cl. + Polyvinyl Chloride.
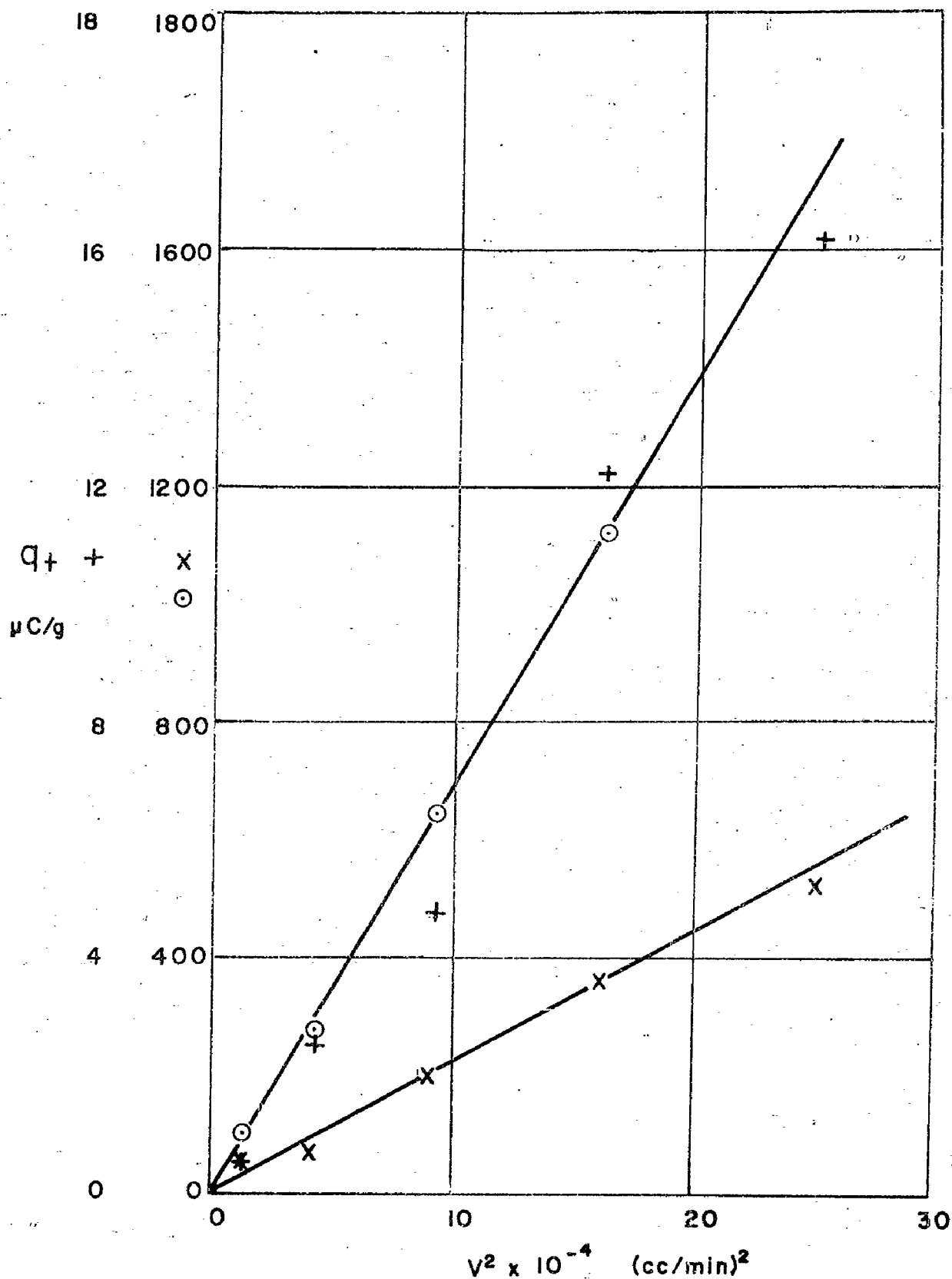
Figure 14. Positive Charge per Gram Positive Deposit, q_+, as a Function of Square of Flow Rate, v. ⊙ MgO, X NH_4Cl, + Polyvinyl Chloride.
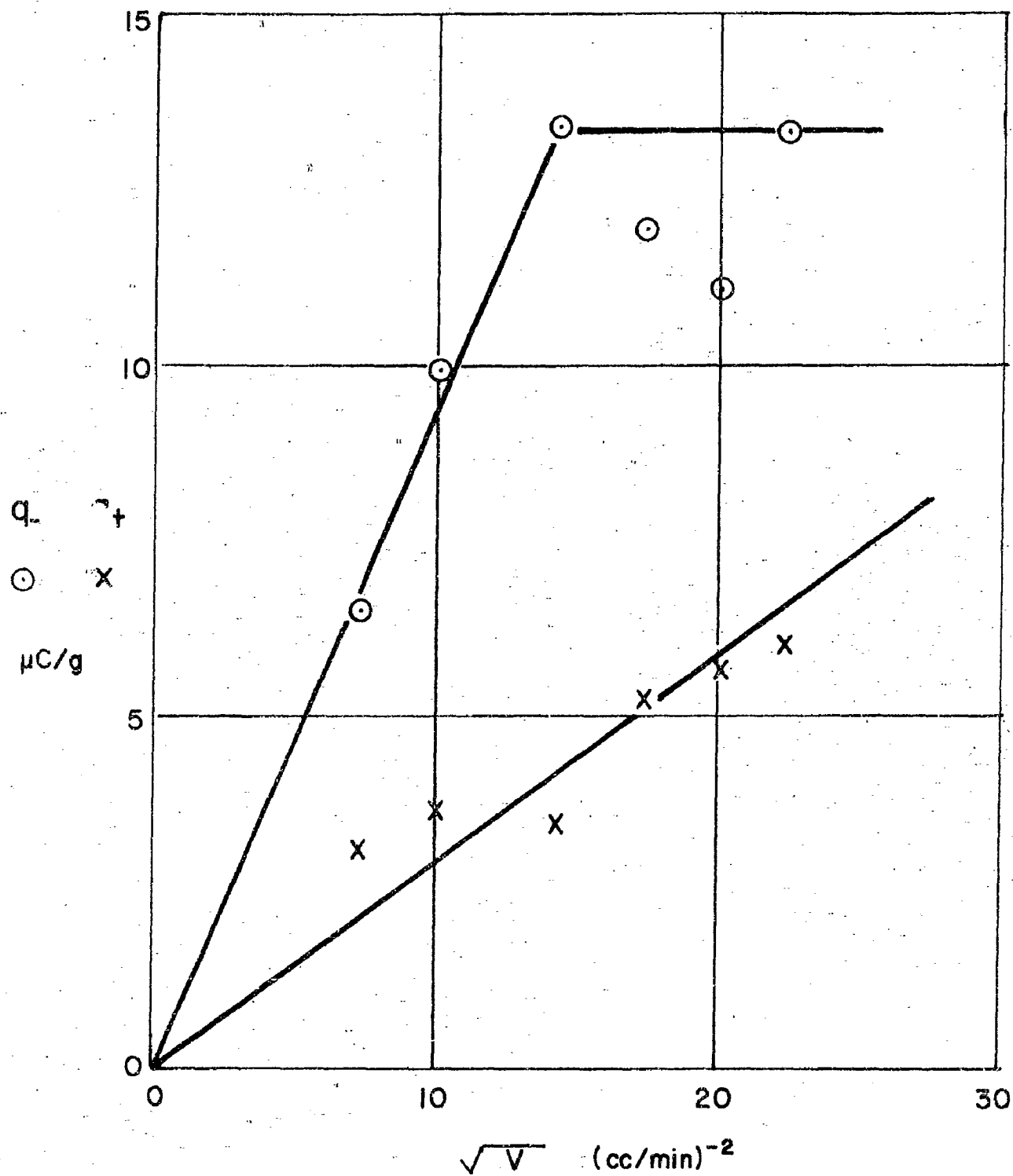
Figure 15. Positive Charge per Gram Positive Deposit, q_+, ($\times$) and Negative Charge per Gram Negative Deposit, q_-, ($\odot$) as Functions of Square Root of Flow Rate, $\sqrt{v}$, for Buerker's Powder.
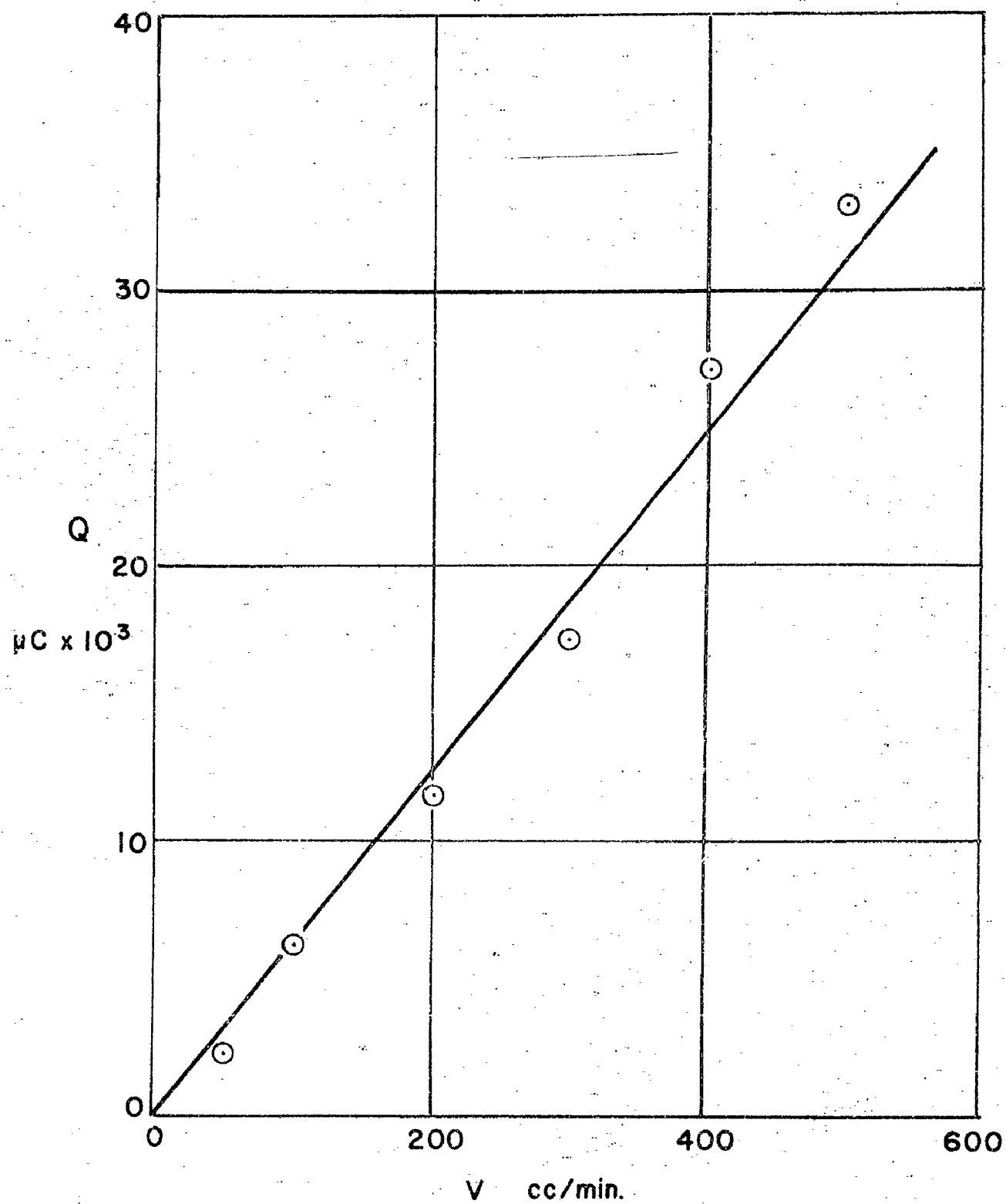
Figure 16.   Total Absolute Charge, Q, as a Function of Flow Rate, v,
for Buerker's Powder.
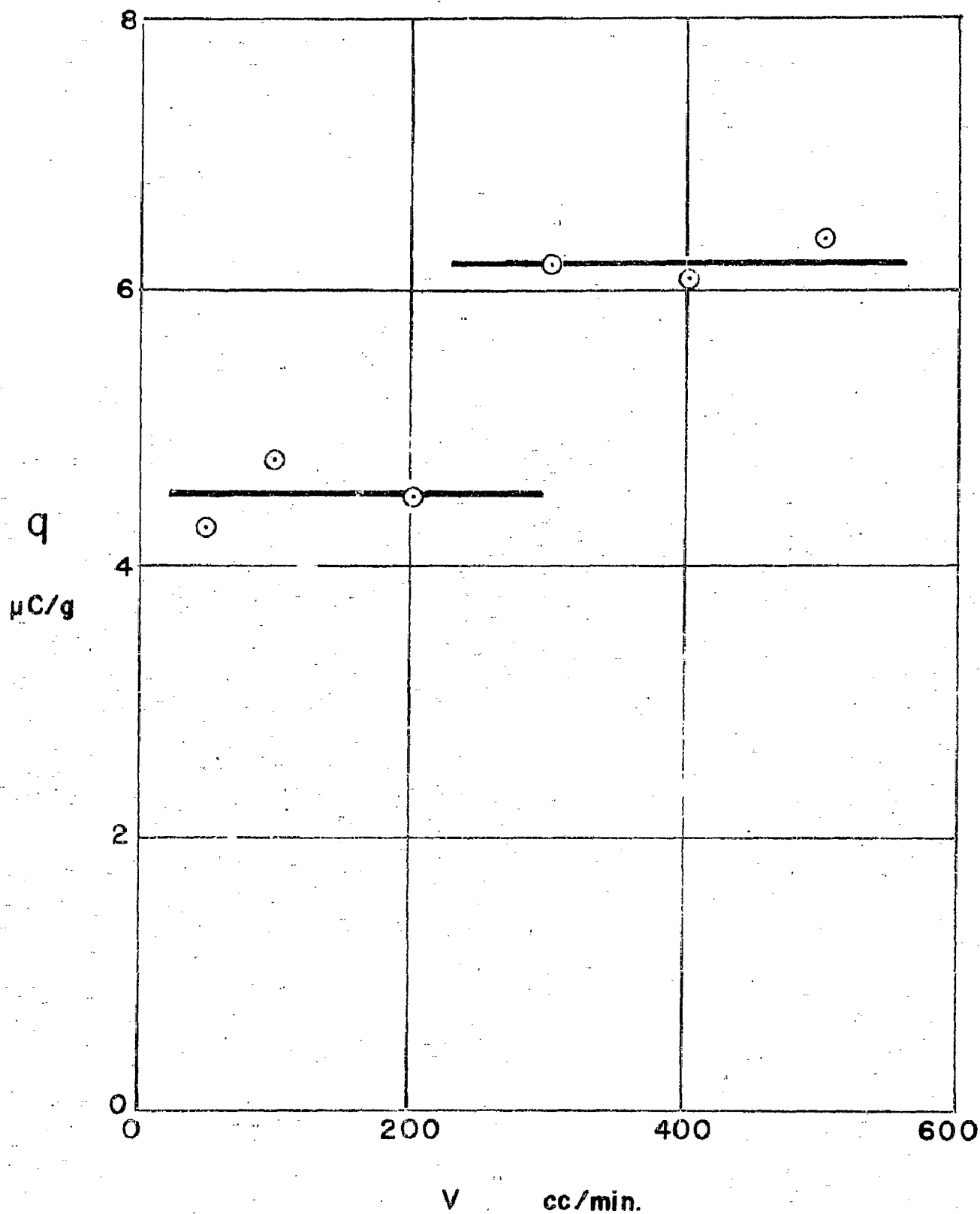
Figure 17. Absolute Charge per Gram, q, as a Function of Flow Rate, v, for Buerker's Powder.
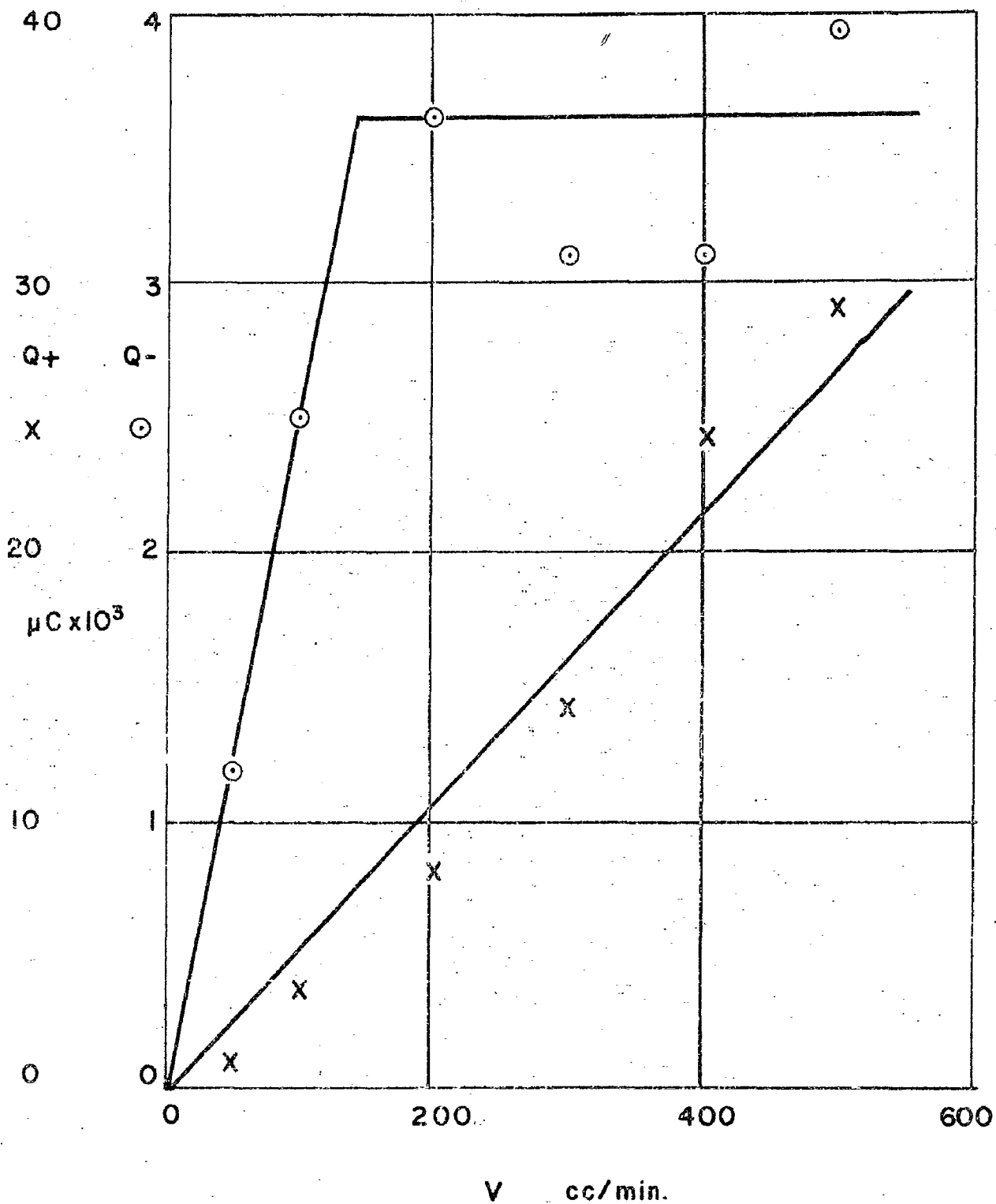
Figure 18. Positive Charge, Q_+, (⊙) and Negative Charge, Q_-, (×) as Functions of Flow Rate, v, for Buerker's Powder.
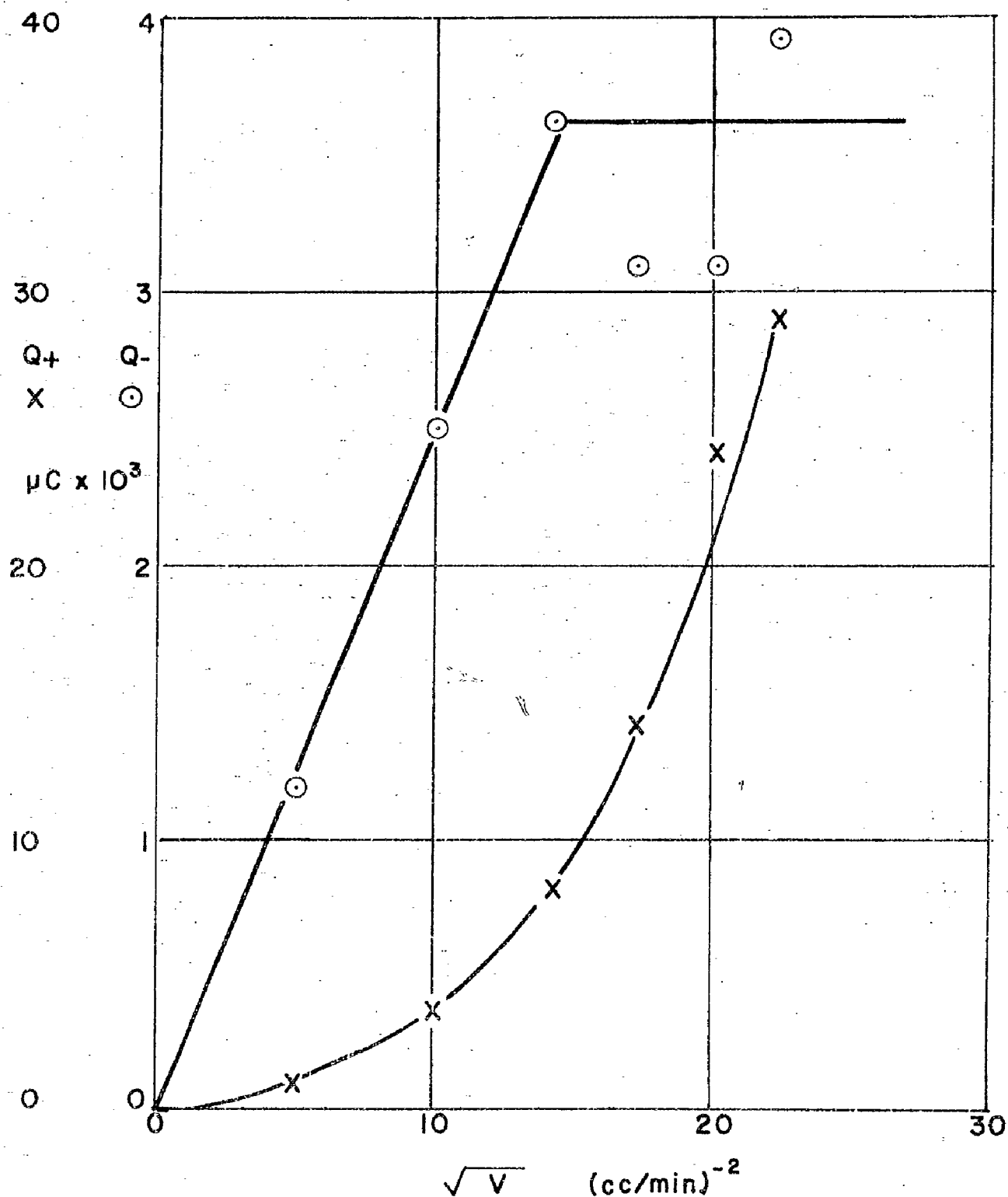
Figure 19. Positive Charge, Q_+, ($\odot$) and Negative Charge, Q_- ($\times$) as Functions of Square Root of Flow Rate, $\sqrt{v}$, for Buerker's Powder.

The powder is probably charged before entering the tube, but this initial charge is lost in the tube. Hence, there is no relation between the charge measured and the initial charge of the aerosol.

This result is gratifying to the purpose at hand, the study of charges acquired in the flow through tubes and nozzles, because it obviates the removal of the initial charge as a separate operation. It has some less gratifying consequences to such data reported in the literature as were obtained by sampling through a hypodermic needle at very low flow rates. Accordingly, such data may be too low by many orders of magnitude. This subject will be discussed in detail in the Appendix.

The charges per gram of powder at a flow rate of 300 cc/min are summarized in Table 1.

Table 1.   Charges Measured at a Flow Rate of 300 cc/min.

Material	q $\mu C/g$	q_+ $\mu C/g$	q_- $\mu C/g$	Green and Lane[8] $\mu C/g$
MgO	500	400	600	1.6
NH_4Cl	120	50	200	2
Polyvinyl Chloride	5	5	5	
Buerker's powder	6	5	14	

The data quoted by Green and Lane [8] were probably obtained at a flow rate of 0.1 cc/min. Sachsse [1] has reported a value of 1.7×10^9 $\mu C/g$ for MgO powder stirred up by blowing. This value is much higher than ours but not incredibly high. At 500 cc/min we found much higher charges than those given in Section 5 and in Table 1, of the order of $5 \times 10^4 \mu C/g$, probably as a result of reduced agglomeration at this high flow rate.

A comparison between the different materials shows that the charge is very much affected by agglomeration. The materials are given in Table 1 in order of increasing agglomeration. According to Sachsse [1]

the charge per particle is proportional to the surface area, and q should therefore be inversely proportional to the particle size. This factor is small, however, as compared to the effect of neutralization of charges in the agglomerates.

The average charge is certainly small as compared to the highest charges in a random distribution. The most highly charged particles are partic- ularly likely to agglomerate. These two factors reduce the charges measured very much below the average charges in the unagglomerated powder and enormously as compared to the highest charges.

Our charge values are up to four orders of magnitude larger than those generally considered in aerosol theory. Yet, our data are averages after agglomeration. A still higher average, 1.7×10^9 µC/g, has been given by Sachsse[1] for MgO. Sachsse's work is discussed in the Appendix. It is well possible that charges of this magnitude may occur before agglomeration. If such is the case, the theory of aerosols needs some drastic modification with respect to the role attributed to electrostatic charges and electrostatic forces.

No attempt will be made at interpreting the empirical relations between charge and flow velocity. Additional information is required for the interpretation. Such information will be collected in the application of the charge analyzer within the investigation presented in Section 1, for which it was constructed.

6. CONCLUSION

The test results indicate that our charge analyzer meets the require- ments given in Section 1. It is convenient enough to work with in order to permit collection of data on the scale required in systematic work. It has an accuracy well compatible with its purpose. It permits measure- ments over wide ranges of charge and flow rate. The main limitation is its sensitivity to humidity, inherent with measurements at high resis- tances. On the other hand, it is necessary in the flow of powders through pipes and nozzles to keep the humidity low in order to prevent caking of the powder.

The test results show that the charge measured is all acquired in the flow through the inlet tube and bears no relation to the charge and charge distribution of the powder before entering the inlet tube. This facilitates the measurements of charges acquired in the flow through tubes. By the

same token it throws suspicion on data obtained by sampling of aerosols
through narrow tubes or rectifying slits. It appears that failure to
recognize this effect has led to gross underestimates of the magnitude
of charges on powder particles and, as a consequence, of the contribution
of electrostatic charges to agglomeration of powder and aerosol particles.

REFERENCES

1. H. Sachsse, Ann. Physik 14 (1932), 396.

2. J. G. Miller, H. Heinemann and W. S. W. MaCarter, Science 107 (1948), 144.

3. T. G. Owe Berg, Aerojet-General Corp., Ordnance Division, Downey, California, Special Report No. R-444 (1961).

4. T. G. Owe Berg and T. A. Gaukler, Aerojet-General Corp Ordnance Division, Downey, California, Special Report No. 0395-04(05)SP, March 1963.

5. T. G. Owe Berg, Aerojet-General Corp., Ordnance Division, Downey, California, Special Report No. R-385-3 (1960).

6. J. H. Nash, G. G. Leiter and A. P. Johnson, General Mills Electronic Group, St. Paul, Minn., Contract No. DA-18-405-CML-824, 7th Quarterly Progress Report, May 1962.

7. K. Bürker, Ann. Physik 1 (1900), 474.

8. H. L. Green and W. R. Land: Particulate Clouds: Dusts, Smokes and Mists, Princeton, 1957

APPENDIX

REVIEW OF THE LITERATURE

The literature on the subject of electrostatic charges and their effects upon aerosols has been reviewed by Green and Lane[1]. In the following that review will be supplemented and extended with a view to the results and conclusions presented in this report.

There are two main techniques for measuring electrostatic charges. Both are based upon the observation of individual particles and upon a relation between particle size and deflection in an electric field. The oldest and most extensively used method is that used by Millikan and others for the determination of the charge of an electron. The particle is then suspended in a vertical field that is adjusted so as to bal ance the force of gravity. In a variation of this method, the particle falls freely in a horizontal electric field, and the deviation of its path from the vertical is measured. A special variant, using an alternating field, is known in this country as the Hopper-Laby method. The other method uses an indirect method for the determination of the trajectories of the particles in a horizontal field. In the instrument developed by Rohmann and Gillespie and Langstroth,[1,2], the particles are collected on the electrodes and the deviation of the trajectory from the vertical is calculated from the location of the particle on the electrode. In the instrument developed by DallaValle et al[1,3,4], the density decay of a beam of particles is measured along its direction by means of light scattering and a photoelectric cell. This method is, of course, limited to aerosols of a uniform particle size, since the light scattering does not distinguish between number of particles and size of particles.

The instruments of Gillespie and Langstroth and of DallaValle are described fairly completely in the book by Green and Lane[1]. In both cases, it is essential that the particles have a known initial velocity perpendicularly to the field and no velocity component in the direction of the field. It is therefore necessary to rectify the flow and to avoid turbulence. This problem has been solved, in both cases, by sucking the aerosol through a hypodermic needle at a small flow rate and by providing a sheath of air around it as it emerges from the needle, which has the same linear flow rate in the space between the electrodes as that of the aerosol in the hypodermic needle. Were it not for this sheath of air, the aerosol would expand and acquire a velocity component in the direction of the field.

The flow velocity in the hypodermic needle is of the order of 0.1 cc/min. These instruments have yielded charges of the order given in Table 1 of Section 6, 1 or $2\mu C/g$ for q_+ and q_-.

The method of observing the trajectories of individual particles has been used by numerous investigators. In most cases of study of aerosols, the aerosol is sampled through a hypodermic needle and introduced into the instrument. The results are not noticeably different from those just quoted. Of considerably greater interest are the investigations, in which the aerosol has been generated in immediate vicinity of the measuring chamber. Outstanding among these is an investigation by Sachsse[5]. In these experiments, powders were stirred up, by blowing air at them, in a container that was connected with the measuring chamber through a simple hole in the bottom. The sketch of the apparatus given in Sachsse's paper indicates that the hole had a large diameter as compared to the thickness of the bottom and as compared to the field of view of the observation microscope. Hence, it may be assumed that many particles fell through the hole without hitting the edge. Sachsse reported values of q_+ and q_- of 5×10^{13} esu/g = 1700 C/g. In Sachsse's experiments, there was no rectification of flow.

Similar experiments have been reported by Kunkel and Hansen[1, 6-8]. The powder was blown off a spoon in a chamber immediately above the observation chamber and fell through a hole in the bottom, just as in Sachsse's experiment. However, there was a channel of unspecified dimensions, terminated by a slit of 1×5 mm^2 opening and 0.2 mm thick, between the two chambers. Furthermore, the slit was made of glass. It can be surmised that most of the particles hit the slit edge. The average charges were of the order of $1 \mu C/g$ with a few small particles carrying up to $5 \mu C/g$.

It is hard to evaluate an instrument or an experimental technique on the basis of a brief description and without actually testing it. The case at hand is comparatively simple, however, because we have investigated the flow of the aerosol through a sampling tube very much the same as those used by Gillespie and Langstroth and by DallaValle et al, who did not, and could not, do this because of the requirement of laminar flow imposed by their measuring technique. We have found that the charge measured depends upon the flow rate, and that the charge measured is all acquired in the sampling tube. This result pertains to the sampling as such and is equally applicable to all measuring techniques that may be employed after sampling.

The charge values given by those investigators [1, 2-4, 9, 10] are probably highly accurate, but they pertain to the sample in the analyzer and are not related to the charges in the initial aerosol.

The results of Kunkel and Hansen and others using similar techniques, are more difficult to evaluate. Whenever a rectifying device is in the path of the aerosol, the aerosol particles will collide with its surface. Otherwise it would not rectify the flow. It is conceivable that it takes time or a number of collisions to affect the charge of a particle, and that a short slit may therefore have much less effect than a long narrow tube. However, the charge values given by Kunkel[7] are similar to those given by Gillespie and Langstroth and by DallaValle et al, and they are smaller than Sachsse's values by a factor of 10^9. Sachsse did not use a rectifying device. The effect of the slit seems to have bothered Kunkel and Hansen[6], who refer to the width of the slit as a critical factor.

It follows from this discussion that sampling through narrow tubes and rectification of flow may be ruinous to charge measurements with aerosols. Before giving credence to values obtained under such conditions, it should be demanded that the effects of sampling and rectification be adquately appraised.

REFERENCES

1. H. L. Green and W. R. Land: Particulate Clouds: Dusts, Smokes and Mists, Princeton, 1957.

2. T. Gillespie and G. O. Langstroth, Can. J. Chem. 30 (1952) 1056.

3. J. M. DallaValle, C. Orr and B. L. Hinkle, Brit. J. Appl. Phys. 5 (1954), 5198.

4. B. L. Hinkle, C. Orr and J. M. DallaValle, J. Colloid Sci. 9 (1954) 70.

5. H. Sachsse, Ann. Physik 14 (1932), 396.

6. W. B. Kunkel and J. W. Hansen, Rev. Sci. Instr. 21 (1950) 308.

7. W. B. Kunkel, J. Appl. Phys. 21 (1950), 822.

8. L. B. Loeb: Static Electrification, Berlin-Göttingen 1958

9. T. Gillespie, Proc. Roy Soc. A216 (1953), 569.

10. T. Gillespie in E. G. Richardson (Edit.) Aerodynamic Capture of Particles, New York 1960. 44.